Post-Chornobyl Thyroid Cancers in Ukraine. Report 1: Estimation of Thyroid Doses

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About 1.8 EBq of ^{131}I was released into the atmosphere during the Chornobyl accident that occurred in Ukraine on April 26, 1986. More than 10% of this activity was deposited on the territory of Ukraine. Beginning 4–5 years after the accident, an increase in the incidence of thyroid cancer among children, believed to be caused in part by exposure to ^{131}I, has been observed in different regions of Ukraine. A three-level system of thyroid dose estimation was developed for the reconstruction of thyroid doses from ^{131}I for the entire population of Ukrainian children aged 1 to 18 at the time of accident: (1) At the first level, individual doses were estimated for the approximately 99,000 children and adolescents with direct measurements of radioactivity in the thyroid (so-called direct thyroid measurements) performed in May–June of 1986; (2) at the second level, group doses by year of age and by gender were estimated for the population of 748 localities (with 208,400 children aged 1–18 in 1986) where direct thyroid measurements of good quality were performed on some of the residents; and (3) at the third level, group doses by age and by gender were estimated for the population of the localities where no thyroid measurements were made in 1986. The third-level doses were then aggregated over the population of each oblast. Data, models and procedures required for each level of thyroid dose estimation are described in the paper. At the first level, individual doses were found to range up to 27,000 mGy, with geometric and arithmetic means of 100 and 300 mGy, respectively. At the second level, group doses were found to be highest for the younger children (aged 1 to 4 years); doses for the older children (aged 16 to 18 years) were 3.5 times smaller. At the third level, average population-weighted doses were found to exceed 35 mGy in the five northern oblasts closer to the Chornobyl reactor site; to be in the 14- to 34-mGy range in seven other oblasts, Kyiv city and Crimea; and to be less than 13 mGy in all other oblasts.
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INTRODUCTION

About 1.8 EBq of ^{131}I was released to the atmosphere during the Chornobyl[2] accident that occurred in Ukraine on 26 April 1986 (*1*). It has been estimated, using an atmospheric transport model (*2*), that approximately 11% of this activity was deposited on the territory of Ukraine.[3] Consumption of fresh milk contaminated with ^{131}I was the main source of thyroid irradiation for the residents of contaminated areas. Beginning 4–5 years after the accident, an unusually high incidence of thyroid cancer among children and adolescents exposed to ^{131}I was observed in the contaminated regions of Ukraine (*3–9*), Belarus (*1, 10–14*) and Russia (*15–17*).

Other radioactive isotopes of iodine (notably ^{132}I, ^{133}I and ^{135}I) and precursor radionuclides (^{131m}Te and ^{132}Te) were also released and could contribute to the thyroid dose. Previous studies indicate that the thyroid doses produced by these radionuclides were a relatively small fraction of the total thyroid dose for most people (*18, 19*). This paper is therefore focused on a detailed evaluation of thyroid doses from ^{131}I.

The investigation of the high incidence of thyroid cancer

[2] Standard Ukrainain spellings of place names are used in this paper. The most noticeable differences are for the site of the accident and the nation's capital, Kyiv, but the names of other locations also differ from those used in previously published papers.

[3] I. Likhtarev, N. Talerko, A. Bouville, P. Voillequé, N. Luckyanov, A. Kuzmenko and I. Shedemenko, Reconstruction of ^{137}Cs and ^{131}I Radioactive Contamination of Ukraine caused by the Chornobyl Accident using Atmospheric Transport Modeling. Draft report available at http//dceg.cancer.gov/radia.html.

among populations that were exposed to radioiodine after the Chornobyl accident consists of two components:

1. Retrospective assessment of the thyroid dose for individuals and for groups of people aggregated according to age, gender and residence from the time of the accident until the end of June 1986.
2. Assessment of the risk of thyroid cancer caused by radiation dose to the thyroid. This assessment can be made in the framework of three types of epidemiological studies: cohort (*20, 21*), case–control (*11*) and ecological (*3, 22*).

The present publication is devoted to a detailed estimation of the thyroid doses from ^{131}I for the entire Ukrainian population and supports an associated ecological analysis of the observed thyroid cancer morbidity.

The estimation of thyroid doses resulting from the Chornobyl accident was initiated in May–June 1986 (*23*). That assessment was based on the ^{131}I activities measured in the thyroids of exposed individuals. The measurements from which these activity estimates were derived are called direct thyroid measurements. A very simple model, which assumed a single intake of ^{131}I at the time of the accident, was used to calculate the thyroid dose from the measurement of thyroid ^{131}I content. Although these estimates were rather conservative, they helped to define the geographic regions with the highest thyroid doses. It was expected that populations of those regions would have the highest risk of developing radiation-induced thyroid cancers.

Since 1986, there have been many revisions of the initial dose assessments with the aim of improving their realism and reliability. Different methodologies have been developed or improved for the estimation of the thyroid doses received by people for whom there were direct thyroid measurements in May–June 1986, as well as those received by people without such measurements (*14, 24–28*).

This research was stimulated by several large-scale epidemiological projects that surveyed childhood thyroid cancer in Ukraine (*21, 29*). These projects were initiated about 1996. Detailed ecological models of radioiodine transfer along food chains (*30*) were developed and used at that time, and special mesoscale models of atmospheric transfer of radionuclides have been improved (*2*). Results of large-scale interviewing were used to obtain information on the residential history and dietary habits of the surveyed cohort members.

In the current thyroid dosimetry system, there are three levels of dosimetry support for different types of epidemiological research. The first level (individual thyroid doses for cohort members) is used in a classical cohort study (*21, 30*). The second and third levels are used in ecological studies to estimate group doses for settlements, raions[4] or

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[4] Raion is an administrative unit within an oblast. Usually there are 10 to 20 raions in an oblast. The raion is comparable to a county in the United States, while the oblast is comparable to a state.

oblasts, taking into account the gender and age of the inhabitants. Data, models and procedures required for the estimation of individual doses (first level) and of group doses (second and third levels) are described in this paper. Dose estimates are presented for people who were aged ≥ 1 to 18 years and who lived in any part of Ukraine at the time of the accident. Infants who were less than 1 year old at the time of the accident are not considered in this paper. Although there were many measurements of thyroid activity performed in May–June 1986, few of these were performed on very young children.

An analysis of the distribution with time and location of the thyroid cancer morbidity for the residents of Ukraine who were aged 1 to 18 years at the time of the accident will be submitted for publication in the near future. That analysis will consist of an assessment of the age-dependent changes in the background thyroid cancer morbidity for the Ukrainian population and an assessment of the absolute and relative risks of the radiation-induced thyroid cancer. The latter will use the thyroid dose estimates presented here.

MATERIALS AND METHODS

This section presents the methods used for thyroid dose calculations, beginning with the general equations for estimation of the time-dependent uptake of ^{131}I by the thyroid and a summary of the ecological model that defines the variation with time. Details of the ecological model and its parameters are included in an Appendix. The scope of the program of direct thyroid measurements is described and the link between the modeled uptakes and the observed thyroid activities is discussed. This is followed by a discussion of the three levels of thyroid dose assessment, starting with estimates of individual dose obtained from direct thyroid measurements. Then we present the techniques used to estimate settlement-specific doses for age and gender groups who resided in locations where direct thyroid measurements were made for some but not all of the children. Methods for the third level, doses estimated for locations where no measurements were performed, are presented last.

General Equations

The variation with time of the ^{131}I activity in the thyroid $Q_{a,s}(t)$ (Bq) for a subject of age a and gender s is defined by two main processes: (1) uptake of ^{131}I by the thyroid, which is described by a function $U_{a,s}(t)$ (Bq day^{-1}), and (2) excretion of ^{131}I from the thyroid, which is assumed to be exponential. It is characterized by the effective constant of elimination of ^{131}I from the thyroid, λ_a^{ef} (day^{-1}) (*31, 32*), which is the sum of the biological elimination constant, λ_a^{biol} (day^{-1}), and of the radioactive decay constant of ^{131}I, λ_1 (day^{-1}). Therefore, the function $Q_{a,s}(t)$ can be described as

$$Q_{a,s}(t) = \int_0^t U_{a,s}(\tau) \cdot e^{-\lambda_a^{ef} \cdot (t-\tau)} \, d\tau. \qquad (1)$$

The absorbed thyroid dose, $D_{a,s}^{th}$(Gy), received until time T after the accident, is

$$D_{a,s}(T) = \frac{\alpha}{M_a} \int_0^T Q_{a,s}(t) \, dt = \frac{\alpha}{M_a} A_{a,s}(T), \qquad (2)$$

where α is the energy absorbed in the thyroid due to the radioactive decay of a unit activity of ^{131}I during 1 day (J Bq^{-1} day^{-1}); M_a is the age-dependent thyroid mass (kg), averaged for boys and girls (*31, 32*); $A_{a,s}(T)$ is the time-integrated activity (Bq day) of the ^{131}I content in the thyroid (during the time period from 0 to T) for a subject of age-gender group a-s.

TABLE 1
Summary of Direct Thyroid Measurements Made in Ukraine in 1986 and Used for Thyroid Dose Estimation

	Numbers of direct thyroid measurements				
Description	Females	Males	Gender not recorded	Total	Number of settlements
Persons with individualized thyroid dose estimates	42,203	42,000	14,929	99,132	778
Persons who were evacuated	4,144	4,160	335	8,639	53
Persons not evacuated	38,059	37,840	14,594	90,493	725
Rural areas	20,696	20,418	6,225	47,339	689
Urban areas	17,363	17,422	8,369	43,125	36
Measurements used for second-level thyroid dose estimates	41,867	41,628	[a]	83,495	748
Persons who were evacuated	4,079	4,069	[a]	8,148	51
Persons not evacuated	37,788	37,559	[a]	75,347	697
Rural areas	20,453	20,153	[a]	40,606	661
Urban areas	17,335	17,406	[a]	34,741	36
Measurements used for the development of the relative time-integrated thyroid ^{131}I activity[b]					
Persons who were evacuated	4,069	4,049	[a]	8,118	49
Persons not evacuated	36,899	36,807	[a]	73,706	619
Rural areas	19,566	19,401	[a]	38,967	584
Urban areas	17,333	17,406	[a]	34,739	35

[a] Results for persons whose gender was unknown were not used for second-level estimates, which were made for groups of females and males of the same age in the indicated numbers of settlements.

[b] Direct thyroid measurements from settlements with measurements of children in the reference age interval of 12–14 years.

Ecological Model

The variation with time of the ^{131}I activity in the thyroid, $Q_{a,s}(t)$ in Eq. (1), can be estimated based on an ecological model that describes the transport of ^{131}I through the environment and in people. The model takes into account inhalation of contaminated air, the processes of ^{131}I deposition on ground and vegetation, transfer of ^{131}I into milk, consumption of contaminated foods by humans, and uptake and retention of ^{131}I in the thyroid. The output of the model describes the dynamics of ^{131}I activity in the thyroid during the period of exposure. Most of the ^{131}I release from the Chornobyl reactor occurred during the first few days after April 26, 1986, and radioactive decay limited the period of concern about intakes of ^{131}I in the diet to about 2 months.

Fundamental to the model are measurements and estimates of the radionuclide deposition densities in locations of interest after the accident. The total deposition densities of ^{137}Cs have been measured in settlements throughout Ukraine. The daily deposition densities of ^{131}I have been estimated using a mesoscale atmospheric transport model (2) calibrated using data for ^{137}Cs (also see footnote 2).

Three pathways of ^{131}I intake are considered in the ecological model: inhalation, ingestion of leafy vegetables, and ingestion of milk. The mathematical description of the model, as well as parameter values, is given in the Appendix.

Direct Measurements of ^{131}I Activity in the Thyroid

Direct measurements of ^{131}I activity in the thyroids of 99,132 children and adolescents aged 1 to 18 years were performed between 20 and 40 days after the accident. The persons with direct measurements were identified by an index, k. Their thyroid doses are based on the results of the direct measurements $\tilde{Q}_{k,a,s}$ (Bq). The methodology of direct thyroid measurements used in Ukraine in April–June of 1986 (population groups, geographic distribution, and descriptions of the measuring devices and of their calibration) has been presented in detail in previous publications (25–27). The results of a special investigation of the reliability and quality of the measurements as well as of the quantification of the uncertainties due to the variability of the age-dependent thyroid mass, the thickness of the overlying tissue, and the position of the detector relative to the

thyroid are given in ref. (28). The results of the thyroid measurements have been corrected to take into account the presence of radiocesium in the human body, considering the age of the subject and the time of measurement after the accident.[5] Use of the direct thyroid measurement results is discussed below.

First Level of Thyroid Dose Estimation

The thyroid dose, $D_{a,s}(T)$ (Gy), using the function $Q_{a,s}(t)$ (Bq) for a subject of age a and gender s who resided in a settlement with a specified level of ^{131}I deposition density, is called *the ecological thyroid dose*. The thyroid dose, calculated taking into account the result of a thyroid activity measurement $\tilde{Q}_{k,a,s}$ (Bq) is called *the instrumentally individualized thyroid dose* and denoted as $D_{k,s,a}(T)$ (Gy). The instrumentally individualized thyroid dose based on information on the individual's diet and behavior is called *the questionnaire-based instrumentally individualized thyroid dose*. The questionnaire-based instrumentally individualized thyroid doses are the most reliable estimates of thyroid dose received by individuals.

Based on the result of the direct thyroid measurement, $\tilde{Q}_{k,a,s}$ (Bq), an *individual scaling factor* for individual k of age a and gender s, K_k^{scal}, can be estimated as: $K_k^{scal} = \tilde{Q}_{k,a,s}/[Q_{a,s}(t_{meas})]$, where $Q_{a,s}(t_{meas})$ is the estimate of the thyroid activity at the time of measurement, t_{meas}, based on the ecological model. It is assumed that the dynamics of ^{131}I activity in the thyroid of individual k are linearly related to the function $Q_{a,s}(t)$. The instrumentally individualized thyroid dose $D_{k,a,s}(T)$ can therefore be calculated as

$$D_{k,a,s}(T) = K_k^{scal}D_{a,s}(T). \tag{3}$$

The first level of thyroid dose estimation is used for approximately 99,000 children with direct thyroid measurements. Table 1 shows the distribution of these measurements by gender, category (evacuated or not), and type of area. Direct thyroid measurements were made for inhabitants of 778 settlements of the Kyiv, Chernihiv and Zhytomyr oblasts, where contamination levels were the highest. This number includes 53 settlements from

[5] I. Likhtarev, L. Kovgan, A. Bouville, N. Luckyanov and P. Voillequé, Estimation of individual doses in Ukraine resulting from Chornobyl accident. Manuscript in preparation.

which people were evacuated. Most of the settlements were in rural areas, but the numbers of persons from rural and urban areas were comparable. For some children, the dose estimation also includes the results of the individual interviews on diet and behavior to yield questionnaire-based instrumentally individualized thyroid doses. For other individuals, reference values of dietary consumption rates and behavior factors, estimated from surveys of other inhabitants of contaminated areas, are used to obtain instrumentally individualized thyroid doses.

Results of interviews of rural and urban inhabitants of Chernihiv oblast (9,500), Kyiv oblast (3,000), and Zhytomyr oblast (2,300) about dietary habits and food consumption rates in May–June 1986 were used for the development of reference age- and gender-dependent consumption rates (see Appendix, Table A2). This survey was undertaken in 1992–1994 as part of the ''Thyroid Passportization''[6] of the affected Ukrainian population and was funded by the Ministry of Chornobyl and Emergency Situation of Ukraine.[7] The questionnaires were developed by the Scientific Center for Radiation Medicine of Ukraine, which managed the project.

Soon after the accident, the inhabitants of the settlements nearest the Chornobyl Nuclear Power Plant were evacuated to other settlements located in Kyiv, Chernihiv and Zhytomyr oblasts. The thyroid doses of people who were evacuated resulted partly from the thyroid exposure at their original location and partly from the thyroid exposure at the place to which they were relocated. Direct thyroid measurements were performed on about 9,500 inhabitants of 53 evacuated settlements. The information on the settlement of evacuation and on the settlement of relocation was taken from the records of measurements and then used in the calculation of the instrumentally individualized thyroid doses for the evacuees.

Individual interviews for more than 13,000 subjects who were less than 18 years old at the time of the accident (or of parents of the subjects who were less than 10 years old) regarding diet and post-accident relocations were conducted in the framework of the Ukrainian-American cohort thyroid study (*20, 21, 30*). Direct thyroid measurements had been performed on all subjects of the cohort. Approvals from the appropriate authorities of the two countries and informed consent from all interviewees had been obtained beforehand to ensure the welfare of the human subjects whose data were used in this study.

The individual doses, $D_{k,a,s}(T)$, are subsequently used for the estimation of the settlement-specific thyroid doses for different age and gender groups (second level of thyroid dose estimation) and to estimate thyroid doses for age and gender groups that are aggregated over the settlements in a raion or oblast (third level of thyroid dose estimation).

Second Level of Thyroid Dose Estimation

The settlement-specific doses for locations where direct thyroid measurements were performed in May–June 1986 are considered in the second level of thyroid dosimetry. In each of the settlements where measurements were made, there were persons whose thyroid activities were not measured. A method for estimating the thyroid doses received by those people is needed. The procedure is based on the relative time-integrated activities of ^{131}I in thyroids of different age and gender groups. The relationships for individuals whose thyroid activities were measured are used to estimate time-integrated thyroid activities for 36 age and gender groups (males and females, yearly age intervals from 1 to 18

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[6] ''Thyroid Passportization'' is the process according to which the thyroid doses were estimated, as mandated by the Ukrainian Law ''On the status and social protection of citizens of Ukraine affected by the Chornobyl accident'' (N 796-XII, 1991). This dose is estimated for the purpose of making decisions about different types of compensation for the affected population.

[7] Ministry of Chornobyl. Complex dosimetric passportization of Ukrainian settlements. Contracts 09-93 and 5/5c-96 with the Scientific Center for Radiation Medicine. Kyiv, 1992, 1996. [in Russian]
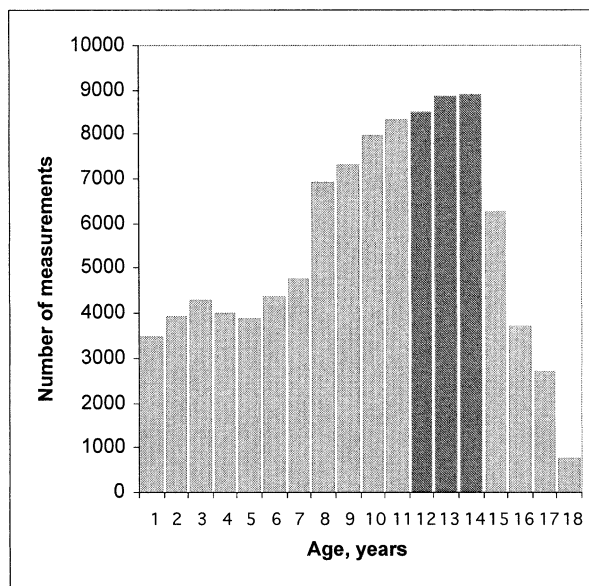

FIG. 1. Distribution of the numbers of direct thyroid measurements made in Ukraine in 1986 according to age at the time of the accident.

years) and then as the basis for dose estimates for unmonitored persons in the same groups who lived in the settlements.

Direct thyroid measurements in Ukraine in 1986 were made with eight types of instruments. Results obtained using devices with γ-ray spectrometry capability are more reliable than those obtained using less sophisticated counting devices. For γ-ray spectrometry measurements, a minimum of four measurements in a settlement were required for inclusion of those results in the analysis. For non-spectrometric instruments, the inclusion criterion was that ten or more measurements were performed in the settlement. These criteria were met for 748 settlements, in which about 83,500 measurements were performed (Table 1).

The distribution of the number of thyroid measurements according to age is shown in Fig. 1.

The largest numbers of direct thyroid measurements were made for children aged 12 to 14 years. This age interval, denoted by a_{ref}, is called the *reference age interval.* There were 619 settlements where direct thyroid measurements were performed on children in the reference age interval who were not evacuated. In addition, measurements in the reference age interval were performed in 49 settlements that were evacuated soon after the accident. The total numbers of persons in these settlements were about 74,000 and 8,000, respectively.

For every person k of age a and gender s with a direct measurement in settlement j, the instrumentally individualized time-integrated activity of ^{131}I in the thyroid is denoted as $A_{k,a,s,j}$ (Bq day) and the relative time-integrated ^{131}I activity in the thyroid, $f_{k,a,s,j}$ is defined as $f_{k,a,s,j} = A_{k,a,s,j}/\hat{A}_{a_{ref},s,j}$, where $\hat{A}_{a_{ref},s,j}$ is the geometric mean of the time-integrated ^{131}I activity in the thyroids of members of the same gender in the reference age interval in settlement j.

Data from all settlements with direct thyroid measurements in the reference age interval were used to calculate geometric mean values (denoted by $f_{a,s}$) of the relative time-integrated activity for each of 36 age-gender groups using the values $f_{k,a,s,j}$ and weights based on the numbers of persons in the reference age interval in the settlement. Statistical comparisons of values of $f_{k,a,s}$ for different subpopulations and different locations were made with the Mann-Whitney test (*33, 34*). There are statistically significant differences between samples of rural and urban children for the majority of age groups. There are also differences between the entire samples of boys and girls for almost all ages. Because of these differences, the distributions of $f_{a,s}$ for different ages, genders and settlement categories are used for thyroid dose estimations at the second level.

TABLE 2
Distribution Parameters for Relative Time-Integrated Thyroidal ^{131}I Activity ($f_{a,s}$)
Estimated for Groups Differing in Age, Gender and Residence Location

Age (years)	Parameters of distributions of relative time-integrated thyroidal activity ($f_{a,s}$)[a]											
	Persons who were not evacuated from their settlements								Evacuated persons			
	Urban areas				Rural areas				Urban and rural areas			
	Females		Males		Females		Males		Females		Males	
	GM	GSD	GM	GSD	GM	GSD	GM	GSD	GM	GSD	GM	GSD
1	0.81	3.26	0.61	3.03	0.58	3.06	0.47	3.23	0.75	2.69	0.82	3.56
2	0.81	2.84	0.62	3.02	0.64	2.83	0.55	2.82	0.84	2.79	0.95	3.23
3	0.77	2.48	0.61	2.82	0.64	2.74	0.54	2.60	0.81	3.61	0.68	5.13
4	0.86	2.35	0.67	2.51	0.70	2.59	0.56	2.88	0.77	4.05	0.74	2.27
5	0.97	2.52	0.86	2.54	0.70	2.63	0.59	2.59	0.80	2.86	0.88	2.88
6	1.03	2.30	0.86	2.27	0.77	2.49	0.66	2.62	0.88	2.83	0.85	3.08
7	1.00	2.13	0.85	2.31	0.75	2.24	0.70	2.35	0.92	3.39	0.76	2.63
8	0.88	2.39	0.79	2.37	0.76	2.36	0.72	2.46	0.71	2.82	0.80	2.28
9	0.91	2.18	0.81	2.15	0.80	2.39	0.79	2.36	0.81	3.08	0.66	2.80
10	0.92	2.17	0.81	2.17	0.81	2.38	0.84	2.19	0.87	2.58	1.10	2.46
11	0.97	2.11	0.91	2.09	0.89	2.20	0.85	2.32	0.80	2.97	0.86	2.44
12	0.95	2.08	0.94	2.14	0.95	2.09	0.90	2.24	0.94	2.84	0.92	2.32
13	1.00	2.11	0.96	2.16	1.01	2.07	1.00	2.24	0.97	2.02	0.95	2.23
14	1.06	2.12	1.11	2.22	1.04	2.12	1.11	2.24	1.06	2.25	1.13	2.44
15	1.11	2.21	1.14	2.28	1.03	2.32	1.21	2.36	1.06	2.39	1.27	3.27
16	1.16	2.37	1.14	2.50	1.04	2.38	1.28	2.51	0.84	3.38	1.10	3.00
17	1.19	2.53	1.12	2.33	1.03	2.35	1.12	2.43	0.76	1.94	1.03	2.98
18	1.12	2.81	1.01	2.96	0.95	2.66	1.07	2.14	0.86	2.31	2.42	1.96

[a] GM = geometric mean; GSD = geometric standard deviation; based upon measurements in Zhytomyr, Kyiv, and Chernihiv Oblasts of Ukraine.

The computed geometric mean values of $f_{a,s}$ and the associated geometric standard deviations for different age and gender groups are given in Table 2 for the three settlement categories. The tabulated values were used to estimate time-integrated thyroid ^{131}I activities $\tilde{A}_{a,s,j}$ for each age-gender group in every settlement j where direct thyroid measurements were performed in 1986:

$$\tilde{A}_{a,s,j} = \tilde{A}_{a_{ref},s,j} \cdot f_{a,s}, \qquad (4)$$

where $\tilde{A}_{a_{ref},s,j}$ is the settlement-specific time-integrated thyroid ^{131}I activity for gender s in the reference age interval in settlement j. Median values of $\tilde{A}_{a_{ref},s,j}$ were estimated from the values of $f_{a,s}$ and of the time-integrated thyroid ^{131}I activity $A_{k,a,s,j}$ for persons with direct thyroid measurements in settlement j.

For settlements where direct measurements were performed, the median thyroid doses $\tilde{D}_{a,s,j}$ for each of 36 age-gender groups in settlement j were calculated using

$$\tilde{D}_{a,s,j} = \frac{\alpha}{M_a} \cdot \tilde{A}_{a_{ref},s,j} \cdot f_{a,s}. \qquad (5)$$

Statistical Properties of the First and Second Levels of Thyroid Dose Estimation

Analyses of the distributions of the measured thyroid activities, $(\tilde{Q}_{k,a,s,j})_t$, made on the same day t, and of the instrumentally individualized time-integrated thyroid activities, $A_{k,a,s,j}$, for different age and gender groups in the same settlement showed that, according to Lilliiefors test (*34*), 70–100% of these distributions for different age-gender groups in various settlements are lognormal. Comparison of the arithmetic and geometric means for samples of measured thyroid activities, $(\tilde{Q}_{k,a,s,j})_t$, for children of the same age and gender in the same settlement showed that their ratio for all samples ranges from 1.35 to 1.53 and is therefore rather stable. Ratios of arithmetic and geometric means for instrumentally in-

dividualized time-integrated thyroid activities $A_{k,a,s,j}$ for people of the same gender, age and settlement, averaged over all settlements, ranged from 1.28 to 1.61 for the various age-gender groups.

Comparisons of results obtained in the first and second levels of thyroid dose estimation show that, for all age-gender groups in the same settlement, the geometric means of thyroid doses $D_{k,a,s,j}$ are very close to the calculated values of $\tilde{D}_{a,s,j}$; the ratios averaged over all settlements and age groups are 1.06 and 1.08 for boys and girls, respectively, with standard deviations of about 0.05. The ratios of the arithmetic means of $D_{k,a,s,j}$ to $(\tilde{D}_{a,s,j})$ in the same sets are substantially greater, with average values over all age groups of about 1.5 and standard deviations of about 0.15. Assuming that the distributions of the estimated thyroid doses of the second level are lognormal, the corresponding arithmetic means of those distributions can easily be derived from the geometric means and geometric standard deviations (*35*).

Third Level of Thyroid Dose Estimation

The third level of thyroid dose estimation provides thyroid dose estimates for settlements where no measurements were performed in 1986; these doses are then aggregated to derive oblast-specific thyroid doses. First, doses are estimated for the raions of three oblasts where thyroid measurements were made in some settlements. Then the procedure of dose estimation for oblasts without thyroid activity measurements is presented. The settlements in the whole territory of Ukraine can be subdivided into three groups:

1. Group 1 includes settlements in Kyiv, Zhytomyr and Chernihiv oblasts where direct thyroid measurements were performed in 1986; the second level of thyroid dose estimation was used for the inhabitants of these settlements. The index j is used to identify settlements of Group 1.
2. Group 2 includes locations in raions where direct thyroid measure-

TABLE 3
Raion-Specific Scaling Factors ($K_{s,raion}^{scal}$) for Raions in Zhytomyr, Kyiv and Chernihiv Oblasts

Oblast	Raion code[a]	Raion name (total number of settlements)	Number of settlements where thyroid activity measurements were made[b]	$K_{s,raion}^{scal}$ Gender	Mean	Standard deviation
Zhytomyr	Z1	Korosten' (112)	53	Female	5.2	3.1
			54	Male	6.2	3.4
	Z2	Luhyny (49)	3	Female	4.7	4.1
			2	Male	8.4	7.9
	Z3	Narodychi (84)	67	Female	2.5	2.1
			64	Male	2.8	2.3
	Z4	Ovruch (157)	116	Female	3.2	2.3
			122	Male	3.9	2.6
	Z5	Olevs'k (61)	10	Female	4.7	2.1
			7	Male	5.4	3.3
Kyiv	K1	Borodianka (47)	29	Female	5.1	3.7
			29	Male	6.9	4.8
	K2	Vyshhorod (59)	40	Female	3.5	1.7
			40	Male	4.8	2.3
	K3	Ivankiv (73)	49	Female	4.8	3.6
			49	Male	6.0	4.3
	K4	Kyievo-Sviatoshyn (51)	3	Female	3.6	1.8
			3	Male	5.9	1.6
	K5	Makariv (68)	42	Female	1.6	0.7
			42	Male	2.1	1.1
	K6	Polis'ke (61)	43	Female	5.5	8.2
			44	Male	10.5	17.7
Chernihiv	Ch1	Kozelet's (111)	82	Female	2.1	1.4
			81	Male	2.5	1.9
	Ch2	Ripky (120)	59	Female	2.1	3.3
			58	Male	2.3	4.4
	Ch3	Chernihiv (128)	85	Female	0.9	1.0
			85	Male	1.3	1.8

[a] These codes are used in Fig. 2 to indicate the locations of the raions within the three oblasts.

[b] Thyroid activity measurements were not made for both genders in all settlements where surveys were conducted.

ments were made, but not in those settlements. The index j* will be used to identify settlements of Group 2.

3. Group 3 includes 25,803 settlements in 21 oblasts of Ukraine and the Republic of Crimea (with about 12 million people aged 1 to 18 years) where no direct thyroid measurements were made. The index j** will be used to identify settlements of Group 3.

For the settlements of Group 2, the estimation of the average time-integrated thyroid ¹³¹I activities $A_{a,s,j*}$ (Bq day⁻¹) is based on dose estimates derived from direct thyroid measurements in settlements in the same raion as the settlement of interest. This was done using a raion scaling factor $K_{s,raion}^{scal}$, which is the average value of the scaling factors for the settlements j of Group 1 in the raion, $K_{s,j}^{scal}$. The scaling factor $K_{s,j}^{scal}$ was defined as the ratio of the time-integrated thyroid ¹³¹I activity estimated using the ecological model, $A_{a_{ref}s,j}^{ecol}$ (Bq day), to the time-integrated thyroid ¹³¹I activity $\tilde{A}_{a_{ref}s,j}$ estimated based on results of direct thyroid measurements using the function $f_{a,s}$. Values of $K_{x,raion}^{scal}$ estimated for each gender in 14 different raions of Kyiv, Zhytomyr and Chernihiv oblasts are given in Table 3. The total number of settlements in each raion and the number of settlements that were used for the development of the scaling factors $K_{s,raion}^{scal}$ also are given in the table.

Table 3 shows that there are rather substantial differences between the time-integrated thyroid ¹³¹I activities for the reference age interval calculated with the ecological model ($A_{a_{ref}s,j}^{ecol}$) and those based upon thyroid measurements $\tilde{A}_{a_{ref}s,j}$. There are several possible reasons for such differences, including inaccuracies in the estimates of ¹³¹I deposition densities, incorrect parameter values in the ecological model, and overestimation of consumption rates of milk and leafy vegetables. The intakes may have been lower than normal due to parental restriction or personal choice.

The thyroid doses for the 36 age-gender groups in the settlements j* of Group 2, where direct thyroid measurements were not performed in 1986, $D_{a,s,j*}$ were estimated using

$$D_{a,s,j*} = \frac{\alpha}{M_a} \cdot \frac{A_{a_{ref}s,j*}^{ecol}}{K_{s,raion}^{scal}} \cdot f_{a,s}. \quad (6)$$

It is assumed for the settlements of Group 3 that personal or parental restriction of dietary intakes was correlated with the level of local deposition of radioactivity. Information on ¹³⁷Cs deposition was used in this analysis because information about general contamination levels was readily available to the public in 1986. The time-integrated thyroid ¹³¹I activity for settlement j**, $A_{a,s,j**}$, was calculated using a scaling factor $K_{s,j**}^{scal}$ that reflects the local ¹³⁷Cs deposition density $\sigma_{Cs,j**}$ (kBq m⁻²). The scaling factor is: $K_{s,j**}^{scal} = B \cdot \sigma_{Cs,j**}^{\beta}$. To estimate the parameters B and β, the correlation between values of scaling factors $K_{s,j}^{scal}$ for all settlements j of Group 1 in Kyiv, Chernihiv and Zhytomyr oblasts, and the measured cumulative ¹³⁷Cs deposition density, $\sigma_{Cs,j}$ (kBq m⁻²), for these settlements was analyzed. Parameters B and β, estimated by fitting, for rural and

TABLE 4
Parameters Used to Estimate Scaling Factors[a] for Settlements Where no Thyroid Activity Measurements were Performed

Location	Gender	B Geometric Mean	B Geometric standard deviation	β Mean	β Standard deviation
Rural areas	Males	0.59	1.1	0.36	0.10
	Females	0.47	1.1	0.36	0.10
Urban areas	Males	0.36	1.5	0.61	0.11
	Females	0.34	1.5	0.58	0.11

[a] The scaling factor for gender s is $K^{scal}_{s,j^{**}} = B \cdot y^{\beta}_{Cs}$, where σ_{Cs} is the ^{137}Cs deposition density for the settlement j^{**}.

urban boys and girls, are given in Table 4. For settlements with low levels of ^{137}Cs deposition(<10 kBq m^{-2}), some calculated values of $K^{scal}_{s,j^{**}}$ were found to be less than 1 and a value $K^{scal}_{s,j^{**}} = 1$ was assumed for these settlements. Thus the thyroid doses for each of 36 age-gender groups in the settlements of Group 3, $D_{a,s,j^{**}}$ are

$$D_{a,s,j^{**}} = \frac{\alpha}{M_a} \cdot \frac{A^{ecol}_{a_{ref},s,j^{**}}}{K^{scal}_{s,j^{**}}} \cdot f_{a,s}. \qquad (7)$$

Oblast-specific thyroid doses for different age-gender groups of Kyiv, Zhytomyr and Chernihiv oblasts were estimated as the sum of population weighted doses averaged over the settlements of Group 1 ($\tilde{D}_{a,s,j}$), Group 2 ($D_{a,s,j^{*}}$) and Group 3 ($D_{a,s,j^{**}}$).[8] In the oblasts with no direct thyroid measurements in 1986, all settlements belong to Group 3. Therefore the oblast-specific thyroid doses for every age and gender group in these oblasts were estimated as the population-weighted doses $D_{a,s,j^{**}}$ averaged over all settlements of the oblast.

MAIN RESULTS AND DISCUSSION

Results for the three levels of thyroid dose estimation are presented in separate sections. The presentation follows the sequence discussed above, beginning with the first-level dose estimates for individuals and moving to settlement-specific and oblast-specific dose estimates.

First Level of Thyroid Dosimetry: Instrumentally Individualized Thyroid Doses

About 99,000 instrumentally individualized thyroid doses were reconstructed for Ukrainian children and adolescents up to 18 years old whose thyroid activities were measured in 1986. These individuals lived in the northern raions of Kyiv, Zhytomyr and Chernihiv oblasts, which were the most contaminated after the Chornobyl accident. Table 5 shows the distributions of individual doses for three age groups according to settlement category and area. The youngest group of children, 1–4 years, received the highest thyroid doses. The highest estimated thyroid dose for any child was 27 Gy. For the unevacuated population, thyroid doses to children from rural areas exceeded those to children from urban areas. The distributions of thyroid doses to each age group of unevacuated children from rural areas

[8] This is an approximation as the sum of medians is not equal to the median of the sum, if the distributions are lognormal. This approximation is considered to be adequate for the purposes of the present analysis.

were similar to those for evacuated children of the same age who were also mainly from rural areas.

The arithmetic mean thyroid dose obtained from the first level of thyroid dosimetry was 300 mGy with a standard deviation of 880 mGy, indicative of the broad range of dose estimates. The geometric mean thyroid dose for the entire group was 100 mGy with a geometric standard deviation of 3.9. About 1% of children in all three settlement categories had estimated thyroid doses that exceeded 10 Gy. Most of these children were aged 1–4 years at the time of the accident. For that age group, there were 15 evacuees in the highest dose category, together with 36 children not evacuated from urban areas and 79 children not evacuated from rural areas.

Second Level of Thyroid Dosimetry: Settlement-Specific Thyroid Doses

Settlement-specific thyroid doses were estimated for 36 age and gender groups in 748 settlements of Kyiv, Zhytomyr

TABLE 5
Distributions of Instrumentally Individualized Thyroid Doses for Age Groups of Children from Settlements in Different Areas

Category, location, and age group	Number of children	Percentage[a] of children with thyroid dose (Gy) in interval ≤0.2	>0.2–1	>1–5	>5–10	>10
Settlements not evacuated						
Rural areas						
1–4 years	9,119	40	43	15	1.7	0.87
5–9 years	13,460	62	31	6.5	0.44	0.07
10–18 years	26,904	73	23	3.7	0.16	<0.01
Urban areas						
1–4 years	5,147	58	33	7.5	1.0	0.70
5–9 years	11,421	82	15	2.6	0.23	0.04
10–18 years	24,442	91	7.7	1.4	0.12	<0.01
Evacuated settlements						
1–4 years	1,475	30	45	22	2.7	1.0
5–9 years	2,432	55	36	8.4	0.58	0.08
10–18 years	4,732	73	23	3.6	0.13	0.02

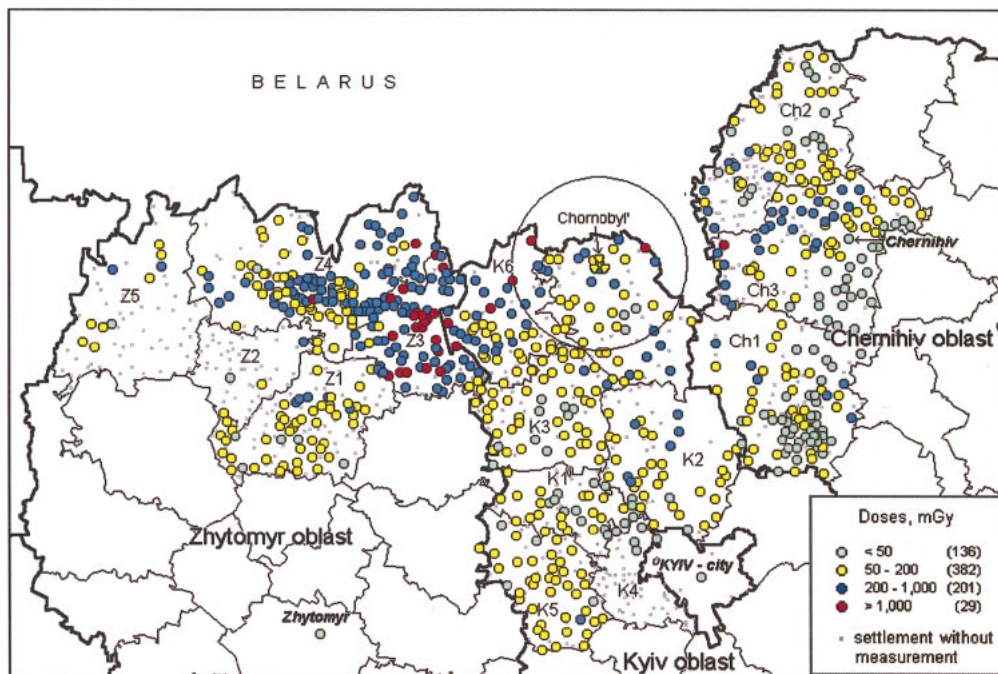[a] Totals for each age group differ from 100% because of rounding of individual entries.

FIG. 2. Estimated thyroid doses (mGy) for children in the reference age interval (12–14 years) for settlements in which direct thyroid measurements were made. The number of settlements in each dose range is given in parentheses. The raion codes (e.g. Z1) are given in Table 3 with the full name of the raion.
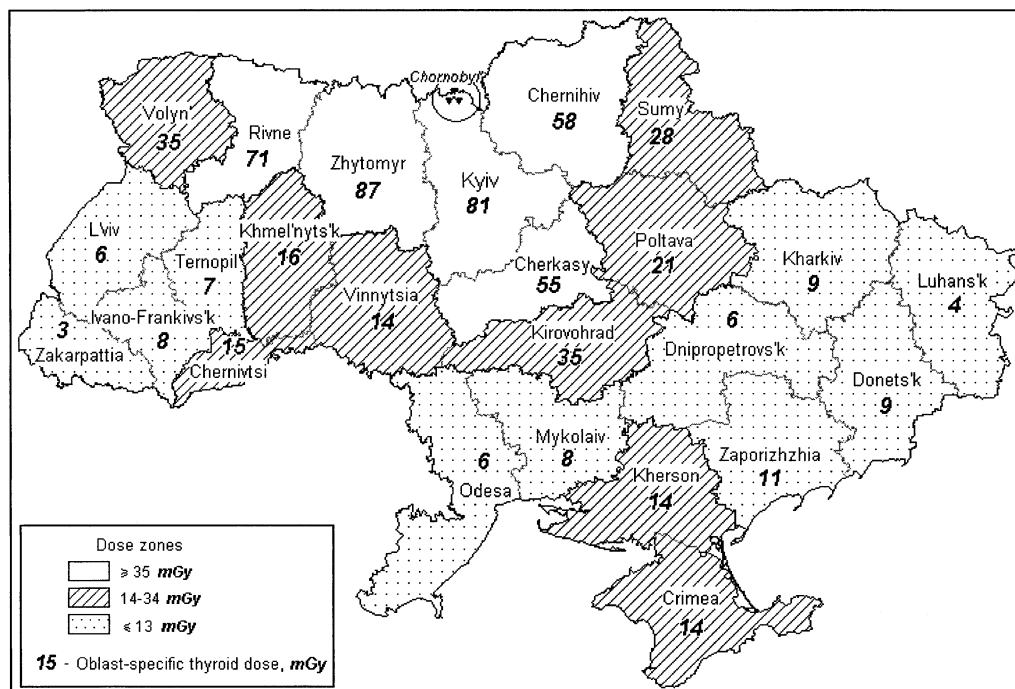

FIG. 3. Oblast-specific thyroid doses (bold numbers, mGy), which are based on thyroid dose estimates for 18 ages and two genders and the populations of those groups in the oblasts. The population group weighted thyroid dose received by children who resided in the city of Kyiv was estimated separately and is not included in the result for Kyiv oblast. The estimated thyroid dose for the city of Kyiv is 32 mGy.

and Chernihiv oblasts where direct thyroid measurements were performed in May–June 1986. Estimated thyroid doses for the reference age group (12–14 years old), averaged over males and females, are shown in Fig. 2. For 518 settlements, the thyroid dose to this group was estimated to be less than 200 mGy; higher doses were estimated for this group in 230 other settlements, including 29 settlements where estimated thyroid doses for the reference group exceeded 1000 mGy. Most of the 29 settlements were in Zhytomyr Oblast. In the cities of Kyiv, Chernihiv and Zhytomyr, the thyroid doses for the reference age group are estimated to be 19, 49 and 12 mGy, respectively. Average thyroid doses were highest for the younger children (aged 1 to 4); thyroid doses for the oldest children (aged 16 to 18) were 3.5 times smaller than those for the younger group. For an age-gender group in any settlement, the estimated group thyroid doses of the second level are close to the geometric means of the instrumentally individualized doses obtained for the same age gender group in the same settlement.

Third Level of Thyroid Dosimetry: Oblast-Specific Thyroid Doses

Oblast-specific thyroid doses were estimated for the 36 age and gender groups in 24 oblasts, Kyiv city and the Crimean Republic. Thyroid doses weighted by the populations of the 36 age and gender groups of each oblast are shown in Fig. 3. Estimated oblast-specific thyroid doses range from 3 mGy for Zakarpattya oblast to 87 mGy for Zhytomyr oblast. The estimated thyroid doses for particular age and gender groups range from 29 to 176 mGy in Zhytomyr oblast, from to 28 to72 mGy in Kyiv oblast, and from 20 to 121 mGy in Chernihiv oblast. Two other oblasts with upper range doses in excess of 100 mGy are Rivne oblast (23–149 mGy) and Cherkasy oblast (18–117 mGy). In all cases, the highest thyroid doses are estimated for children who were 1 or 2 years old at the time of the accident.

Based on the oblast-specific thyroid doses, the entire territory of Ukraine can be subdivided into three zones: (1) a zone of high thyroid doses (>35 mGy): Zhytomyr, Kyiv, Rivne, Chernihiv and Cherkasy oblasts; (2) a zone of moderate thyroid doses (14–34 mGy): Volyn', Vinnytsia, Khmel'nyts'k, Chernivtsi, Kirovohrad, Poltava and Sumy oblasts, Kyiv city, and the Autonomous Republic of Crimea; and (3) a zone of low thyroid doses (≤13 mGy) : the other 12 oblasts of Ukraine. These zones are shown in Fig. 3.

FUTURE WORK

The approaches described for the three levels of thyroid dose estimation summarize the current status of retrospective thyroid dosimetry achieved in Ukraine up to the year 2004. In the framework of the Ukrainian-American cohort thyroid study (*20, 21, 30*), the questionnaire-based instrumentally individualized approach is used to estimate the individual thyroid doses. The other approaches are em-ployed in ecological epidemiological analyses of thyroid cancer incidence after the Chornobyl accident.

At this point, it is appropriate to identify a number of areas of dosimetric research needed for reducing the uncertainty associated with the thyroid dose estimates. These are:

1. Modification of the parameters of iodine metabolism that depend on the level of stable iodine in the diet. This is most important for the condition of iodine deficiency that was prevalent in northern Ukraine at the time of the Chornobyl accident.
2. Clarification of the age-dependent thyroid mass for the children and adolescents of Ukraine at the time of the Chornobyl accident, as influenced by the level of dietary iodine.
3. Reassessment of reference dietary consumption rates, especially for young children, at the time of the accident. This is because restrictions on the consumption of milk and leafy vegetables most likely were applied by parents of those children.
4. Evaluation of the uncertainties in ^{131}I deposition estimates and of the parameter values used in the ecological model.
5. Evaluation of the doses received by children aged <1 year at the time of the accident.
6. Evaluation of the uncertainties in the models used for the three levels of thyroid dose estimation.

APPENDIX

Ecological Model Used for the First Level of Thyroid Dose Estimation: Equations And Parameters

The description of the ecological model is given below for the simple case of a single ground deposition σ_r (Bq m^{-2}) of radionuclide r on the territory of the settlement. The following radionuclides were considered and are listed with the corresponding values of r: [131]I ($r = 1$), [137]Cs ($r = 2$), [134]Cs ($r = 3$), [136]Cs ($r = 4$). In the actual dose calculations, the estimates of daily depositions of radionuclides between April 26 and May 5 are taken into account.

The radionuclide concentration in the thyroid due to the inhalation pathway $Q_{a,s}^{I,inhal}(t)$ was considered only for ^{131}I and calculated as follows:

$$Q_{a,s}^{I,inhal}(t) = \frac{\sigma_1}{v_I} \cdot w_a^{inhal} \cdot K_{inhal}^I \cdot K_{uptake}^1 e^{-\lambda_a^{I,ref.}t}, \qquad (A1)$$

where w_a^{inhal} is the breathing rate for persons of age a, (m^3 day^{-1}), v_r is the dry deposition velocity, (m day^{-1}) for nuclide r, K_{inhal}^I is the fraction of ^{131}I inhalation intake transferred to blood via the lung, K_{uptake} is the uptake of radionuclide r from blood to the thyroid (body), and $\pi_a^{r,ef}$ is the effective elimination rate constant for radionuclide r.

The component of radionuclide activity in the thyroid/body that is due to the consumption of leafy vegetables $Q_{a,s}^{r,veg}$ is

$$Q_{a,s}^{r,veg}(t) = K_{uptake}^r \cdot K_{ing}^r \frac{k_w^r}{M_{biom}} \cdot \sigma_r \cdot w_{a,s}^{veg} \cdot \left[\frac{a_r}{L_1^r - \pi_a^{r,biol}}(e^{-\lambda_a^{r,ef.}t} - e^{-L_1^{r,ef.}t}) + \frac{1 - a_r}{L_2^r - \pi_a^{r,biol}}(e^{-\lambda_a^{r,ef.}t} - e^{-L_2^{r,ef.}t}) \right],$$

$$(A2)$$

where K_{ing}^r is the resorption factor from gastrointestinal to blood for the

TABLE A1
Values of Parameters Used in the Ecological Model to Estimate Uptakes of Radionuclides of Iodine and Cesium (36, 37)

Groups of parameters	Parameter	Units	Symbol	Radionuclide Iodine	Radionuclide Cesium
				Default values	
Grass[a] and leafy vegetables	Half-time of elimination - 1	days	$T_1^{r\,b}$	11	3
	Half-time of elimination - 2	days	$T_2^{r\,b}$	50	50
	Fraction of component - 1	—	a_r	1	0.7
	Fraction of component - 2	—	$1 - a_r$	—	0.3
	Interception factor	—	k_w^r	0.5	0.2
	Culinary factor for leafy vegetables	—	K_{cul}	0.8	0.5
	Deposition velocity	m day^{-1}	v_r	600	—
Cow[c]	Half-time of elimination - 1	days	$T_{cow,1}^{r\,b}$	0.75	1
	Half-time of elimination - 2	days	$T_{cow,2}^{r\,b}$	—	30
	Fraction of compartment - 1	—	Q_{cow1}^r	1	0.2
	Fraction of compartment - 2	—	Q_{cow2}^r	—	0.8
	Transfer factor (cow's milk intake)	days liter^{-1}	TF_r	0.004	0.01
Human	Uptake to blood from lung	—	K_{inhal}^1	0.66	—
	Resorption factor from gastrointestinal to blood for the radionuclide		K_{ing}^r	1	1
	Uptake of radionuclide from blood to the thyroid (I) or body (Cs)	—	K_{uptake}^r	0.3	1

[a] Yield of pasture grass (M_{biom}) is taken to be 0.7 kg m^{-2}.
[b] $T_1 = (\log 2)/L_1^r$; $T_2 = (\log 2)/L_2^r$; $T_{cow,1} = (\log 2)/T_{cow,2}^r = (\log 2)/\lambda_{cow,2}^r$.
[c] Cow's grass consumption rate (w_{grass}^{cow}) is taken to be 40 kg day^{-1}.

radionuclide r; $K_{ing}^r = 1$ (31) for cesium and iodine radionuclides, K_w^r is the interception factor by pasture grass for radionuclide r; M_{biom} is the yield of pasture grass (kg m^{-2}); $w_{a,s}^{veg}$ is the daily consumption of leafy vegetables by a representative of the a-s age-gender group (kg day^{-1}); L_1^r, L_2^r are rate constants of removal of radionuclide r from the grass surfaces by weathering (day^{-1}); $L_1^{r,ef} = L_1^r + \lambda^r$ and $L_2^{r,ef} = L_2^r + \lambda^e$; a_r is the fraction of the contamination that is removed with the coefficient L_1^r; λ_p is the radioactive decay rate constant of radionuclide r (day^{-1}). The milk component of the radionuclide activity in the thyroid/body $Q_{a,s}^{r,m}(t)$ can be calculated as:

$$Q_{a,s}^{r,m}(t) = K_{uptake}^r \cdot K_{ing}^r \frac{k_w^r}{M_{biom}} \cdot \sigma^r \cdot w_{a,s}^{veg} \cdot TF_r \cdot w_{grass}^{cow} \sum_{n=1}^{2} Q_{cow,n}^r \cdot \lambda_{cow,n}^r$$

$$\times \left[\frac{a_r}{\lambda_{cow,n}^r - L_l^r} \left(\frac{e^{-\lambda_a^{r,ef} \cdot t} - e^{-L_1^{r,ef} \cdot t}}{L_1^r - \lambda_a^{r,biol}} - \frac{e^{-\lambda_a^{r,ef} \cdot t} - e^{-\lambda_{cow,n}^r \cdot t}}{\lambda_{cow,n}^r - \lambda_a^{r,biol}} \right) \right.$$

TABLE A2
Milk and Leafy Vegetable Consumption Rates for Different Age-Gender Groups

Age (years)	Milk consumption rate (liters day^{-1}) Rural areas Male	Female	Urban areas Male	Female	Leafy vegetable consumption rate (kg day^{-1}) Rural areas Male	Female	Urban areas Male	Female
1	0.67	0.59	0.39	0.37	0.007	0.006	0.005	0.004
2	0.68	0.58	0.41	0.35	0.016	0.015	0.013	0.010
3	0.70	0.56	0.42	0.34	0.021	0.020	0.017	0.014
4	0.70	0.52	0.35	0.27	0.023	0.021	0.018	0.015
5	0.72	0.50	0.35	0.27	0.025	0.022	0.020	0.016
6	0.74	0.48	0.35	0.27	0.027	0.023	0.021	0.017
7	0.76	0.46	0.35	0.27	0.029	0.024	0.022	0.019
8	0.75	0.45	0.37	0.27	0.029	0.024	0.022	0.019
9	0.75	0.45	0.37	0.27	0.030	0.024	0.023	0.019
10	0.75	0.45	0.37	0.27	0.030	0.024	0.023	0.019
11	0.76	0.44	0.37	0.27	0.031	0.025	0.023	0.019
12	0.82	0.48	0.35	0.25	0.031	0.025	0.023	0.019
13	0.83	0.47	0.35	0.25	0.032	0.025	0.023	0.019
14	0.83	0.47	0.35	0.25	0.033	0.025	0.024	0.019
15	0.83	0.47	0.35	0.25	0.033	0.025	0.024	0.019
16	0.84	0.48	0.38	0.26	0.034	0.025	0.024	0.019
17	0.85	0.47	0.38	0.26	0.035	0.025	0.024	0.019
18	0.85	0.47	0.38	0.26	0.035	0.025	0.025	0.019

TABLE A3
Values of Age-Dependent Metabolic Parameters
Used for Individual Dose Estimations

Age (years)	Thyroid mass (g)	Biological half-time of ^{131}I in thyroid (days)	Inhalation rate (m^3 day^{-1})
1	2.0	15	5.6
2	2.4	18	6.5
3	2.8	19	7.4
4	3.2	20	8.3
5	3.9	23	9.3
6	4.8	28	10
7	5.7	36	11
8	6.6	44	13
9	7.5	51	14
10	8.4	58	15
11	9.3	63	16
12	10	65	17
13	11	66	18
14	12	67	20
15	13	67	20
16	15	67	21
17	16	68	21
18	18	70	22

Metabolic parameters (*31, 32*)

$$+ \frac{1 - a_r}{\lambda_{cow,n}^r - L_2^r} \left(\frac{e^{-\lambda_a^{r,ef} \cdot t} - e^{-L_2^r \cdot t}}{L_2^r - \lambda_a^{r,biol}} - \frac{e^{-\lambda_a^{r,ef} \cdot t} - e^{-\lambda_{cow,n}^r \cdot t}}{\lambda^{r_{cow,n}} - \lambda_a^{r,biol}} \right) \Bigg].$$

(A3)

Here $\lambda_{cow,n}^{r,ef}$ is the effective elimination rate constant for radionuclide r (day^{-1});

$$\lambda_{cow,1}^{r,ef} = \lambda_{cow,1}^r + \lambda^r \quad \text{and} \quad \lambda_{cow,2}^{r,ef} = \lambda_{cow,2}^r + \lambda^r;$$

w_{grass}^{cow} is the daily consumption of pasture grass by the cow (kg day^{-1}); TF_r is the transfer factor for radionuclide r from daily cow's intake to concentration in cow's milk (day liter^{-1}).

The values of the parameters used in the ecological model described above are given in Table A1. The age- and gender-dependent daily consumption rates of milk, $w_{a,s}^m$, and leafy vegetables, $w_{a,s}^{veg}$, that were used in the model are shown in Table A2. Values for the age-dependent thyroid mass, M_a, biological half-time of ^{131}I thyroid elimination, $T_a^{I,biol}$ ($T_a^{I,biol} = \ln 2/\lambda_a^{I,biol}$), and ventilation rate, w_a^{inhal}, used in the model are given in Table A3.

ACKNOWLEDGMENTS

REFERENCES

1. United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources and Effects of Ionizing Radiation,* Report to the General Assembly, with Scientific Annexes. United Nations, New York, 2000.

2. N. Talerko, Mesoscale modeling of radioactive contamination formation in Ukraine caused by the Chernobyl accident. *J. Environ. Radioactivity* (in press).

3. P. Jacob, G. Goulko, W. F. Heidenreich, I. Likhtarev, I. Kairo, N. Tronko, T. Bogdanova, J. Kenigsberg, E. Bugolva, V. Drozdovitch and V. Beral, Thyroid cancer risk to children calculated. *Nature* **392**, 31–32 (1998).

4. I. A. Likhtarev, B. G. Sobolev, I. A. Kairo, N. D. Tronko, T. I. Bogdanova, V. A. Oleinic, E. V. Epshtein and V. Beral, Thyroid cancer in the Ukraine. *Nature* **375**, 365 (1995).

5. N. Tronko, T. Bogdanova, I. Komissarenko, S. Rybakov, A. Kovalenko, O. Epshtein, V. Oliynik, V. Tereshchenko, I. Likhtarev and M. Chepurnoy, The post-Chernobyl incidence of childhood thyroid cancer in Ukraine. In *Radiation and Thyroid Cancer. Proceedings of an International Seminar,* pp. 61–69. EUR 18552 EN, European Commission, Luxembourg, 1999.

6. N. D. Tronko, T. I. Bogdanova, I. V. Komissarenko, O. V. Epstein, V. A. Oliynik, A. Ye. Kovalenko, I. A. Likhtarev, I. A. Kairo, S. B. Peters and V. A. LiVolsi, Thyroid carcinoma in children and adolescents in Ukraine after the Chernobyl accident: Statistical data and clinicomorphologic characteristics. *Cancer* **86**, 149–156 (1999).

7. N. D. Tronko, I. A. Likhtarev, I. A. Kairo and V. I. Shpak, Summary of the 15-year observation of thyroid cancer among Ukrainian children after the Chernobyl accident. In *Chernobyl: Message for the 21st Century, Proceedings of the Sixth Chernobyl Sasakawa Medical Cooperation Symposium, Moscow, Russia, 30–31 May, 2001* (S. Yamashita, Y. Shibata, M. Hoshi and K. Fujimura, Eds.), pp. 77–83. Elsevier, Amsterdam, 2002.

8. B. Sobolev, I. Likhtarev, I. Kairo, N. Tronko, V. Oleynik and T. Bogdanova, Radiation risk assessment of the thyroid cancer in Ukrainian children exposed due to Chernobyl. In *The Radiological Consequences of the Chernobyl Accident, Proceedings of the First International Conference, Minsk, Belarus, 18 to 22 March, 1996* (A. Karaoglou, G. Desmet, G. N. Kelly, and H. G. Menzel, Eds.), pp. 741–748. EUR 16544 EN, European Commission, Luxembourg, 1996.

9. N. Tronko, T. Bogdanova, I. Komissarenko, E. Bolshova, V. Oleynik, V. Tereshchenko, Y. Epshtein and V. Chebotarev, Thyroid cancer in children and adolescents in Ukraine after the Chernobyl accident (1986–1995). In *The Radiological Consequences of the Chernobyl Accident, Proceedings of the First International Conference, Minsk, Belarus, 18 to 22 March 1996* (A. Karaoglou, G. Desmet, G. N. Kelly, and H. G. Menzel, Eds.), pp. 683–690. EUR 16544 EN, European Commission, Luxembourg, 1996.

10. T. Abelin, J. Averkin, A. Okeanov and J. Bleuer, Thyroid cancer in Belarus: The epidemiological situation. In *The Radiological Consequences of the Chernobyl Accident, Proceedings of the First International Conference, Minsk, Belarus, 18 to 22 March 1996* (A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel, Eds.), pp. 727–730. EUR 16544 EN, European Commission, Luxembourg, 1996.

11. L. N. Astakhova, L. R. Anspaugh, G. W. Beebe, A. Bouville, V. V. Drozdovitch, G. Garber, Y. I. Gavrilin, V. T. Khrouch, A. V. Kuvshinnikov and M. A. Waclawiw, Chernobyl-related thyroid cancer in children of Belarus: A case–control study. *Radiat. Res.* **150**, 349–356 (1998).

12. E. P. Demidchic, I. M. Drobyshevskaya, E. D. Cherstvoy, L. N. Astakhova, A. E. Okeanov, T. V. Vorontsova and M. Germanchuk, Thyroid cancer in children in Belarus. In *The Radiological Consequences of the Chernobyl Accident, Proceedings of the First International Conference, Minsk, Belarus, 18 to 22 March 1996* (A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel, Eds.), pp. 677–682. EUR 16544 EN, European Commission, Luxembourg, 1996.

13. J. Kenigsberg, E. Buglova, H. Paretzke and W. Heidenreich, Perspectives of development of thyroid cancer in Belarus. In *The Radiological Consequences of the Chernobyl Accident, Proceedings of the First International Conference, Minsk, Belarus, 18 to 22 March, 1996* (A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel, Eds.), pp. 771–775. EUR 16544 EN, European Commission, Luxembourg, 1996.

14. G. N. Sushkevich and A. F. Tsyb, Eds., *Medical Consequences of the Chernobyl Accident, Results of the IPHECA Pilot Projects and Related National Programmes, Scientific Report.* International Pro-

gramme on the Health Effects of the Chernobyl Accident (IPHECA), World Health Organization, Geneva, 1996.

15. A. F. Tsyb, E. M. Parshkov, V. V. Shakhtarin, V. F. Stepanenko, V. F. Skvortsov and I. V. Chebotareva, Thyroid cancer in children and adolescents of Bryansk and Kaluga regions. In *The Radiological Consequences of the Chernobyl Accident, Proceedings of The First International Conference, Minsk, Belarus, 18 to 22 March, 1996* (A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel, Eds.), pp. 691–697. EUR 16544 EN, European Commission, Luxembourg, 1996.

16. V. Ivanov, A. Gorsky, V. Pitkevitch, A. Tsyb, E. Cardis and H. Storm, Risk of radiogenic thyroid cancer in Russia following the Chernobyl accident. In *Radiation and Thyroid Cancer. Proceedings of an International Seminar,* pp. 89–96. EUR 18552 EN, European Commission, Luxembourg, 1999.

17. V. K. Ivanov, A. I. Gorski and A. F. Tsyb, Dynamics of thyroid cancer incidence in Russia following the Chernobyl accident. *J. Radiol. Prot.* **19**, 305–318 (1999).

18. M. Balonov, G. Kaidanovsky, I. Zvonova, A. Kovtun, A. Bouville, N. Luckyanov and P. Voillequé, Contributions of short-lived radioiodines to thyroid doses received by evacuees from the Chernobyl area estimated using early *in-vivo* measurements. *Radiat. Prot. Dosim.* **105**, 593–599 (2003).

19. Y. Gavrilin, V. Khrouch, S. Shinkarev, V. Drozdovitch, V. Minenko, E. Shemiakhina, A. Ulanovsky, A. Bouville and N. Luckyanov, Individual thyroid dose estimation for a case-control study of Chernobyl-related thyroid cancer among children of Belarus. Part 1: ^{131}I, short-lived radioiodines (^{132}I, ^{133}I, ^{135}I), and short-lived radiotelluriums (^{131m}Te and ^{132}Te). *Health Phys.* **86**, 565–585 (2004).

20. M. D. Tronko, O. O. Bobylyova, T. I. Bogdanova, O. V. Epshtein, I. A. Likhtaryov, V. V. Markov, V. A. Oliynyk, V. P. Tereshchenko, V. M. Shpak and P. Voillequé, Thyroid gland and radiation (Ukrainian-American Thyroid Project). In *Radiation and Humankind. Proceedings of the First Nagasaki Symposium of the International Consortium for Medical Care of Hibakusha and Radiation Life Science, Nagasaki, Japan, 21–22 February, 2003,* pp. 91–104. International Congress Series 1258, Elsevier, Amsterdam, 2003.

21. V. A. Stezhko, E. E. Buglova, L. I. Danilova, V. M. Drozd, N. A. Krysenko, N. R. Lesnikova, V. F. Minenko, V. A. Ostapenko, S. V. Petrenko and L. B. Zablotska, A cohort study of thyroid cancer and other thyroid diseases following the Chernobyl accident: Objectives, design and methods. *Radiat. Res.* **161**, 481–492 (2004).

22. P. Jacob, Y. Kenigsberg, I. Zvonova, G. Goulko, E. Buglova, W. Heidenreich, A. Golovneva, A. Bratilova, V. Drozdovitch and H. Paretzke, Childhood exposure due to the Chernobyl accident and thyroid cancer risk in contaminated area of Belarus and Russia. *Br. J. Cancer* **80**, 1461–1469 (1999).

23. A. E. Romanenko, O. A. Pyatak, A. Z. Zapesochnui and M. V. Shcherbakova, Eds., *Medical Aspects of Accident on Chernobyl NPP. Materials of Scientific Conference on May 11–13, 1988.* Zdorov'ya, Kyiv, 1988. [in Russian]

24. I. Likhtarev, L. Kovgan, S. Vavilov, R. Gluvchinsky, Z. Boyko, L. Belayar, V. Repin, V. Berkovsky, N. Novak and G. Sotnikova, Radiation dosimetry passportization of the settlements located on the territories of Ukraine radioactively affected following the Chernobyl accident (including passportization of thyroid doses). *Methodology Recommendations.* Ministry of Health of Ukraine, Kyiv, 1996. [in Russian]

25. I. A. Likhtariov, N. K. Shandala, G. M. Gulko, I. A. Kairo and N. I. Chepurnoy, Exposure doses to thyroid of the Ukrainian population after the Chernobyl accident. *Health Phys.* **64**, 594–599 (1993).

26. I. Likhtarev, G. Gulko, B. Sobolev, I. Kairo, N. Chepurnoy, G. Pröhl and K. Henrichs, Thyroid dose assessment for the Chernigov region (Ukraine): Estimation based on ^{131}I thyroid measurements and extrapolation of the results to districts without monitoring. *Radiat. Environ. Biophys.* **33**, 149–166 (1994).

27. I. Likhtarev, B. Sobolev, I. Kairo, L. Tabachny, P. Jacob, G. Prohl and G. Goulko, Results of large scale thyroid dose reconstruction in Ukraine In *The Radiological Consequences of the Chernobyl Accident, Proceedings of the First International Conference, Minsk, Belarus, 18 to 22 March, 1996* (A. Karaoglou, G. Desmet, G. N. Kelly and H. G. Menzel, Eds.), pp. 1021–1034. EUR 16544 EN, European Commission, Luxembourg, 1996.

28. I. A. Likhtarev, G. M. Gulko, I. A. Kairo, B. G. Sobolev, N. I. Chepurnoy, A. K. Cheban, D. A. Nikonov, I. A. Djachkov, G. Prohl and K. Henrichs, *Reliability and Accuracy of the ^{131}I Thyroid Activity Measurements Performed in the Ukraine after the Chernobyl Accident in 1986.* GSF-Bericht 19/93, Institut fur Strahlenschutz, Munich, 1993.

29. S. Yamashita and Y. Shibata, Eds., *Chernobyl: A Decade, Proceedings of the 5th Chernobyl Sasakawa Medical Cooperation Symposium, Kyiv, Ukraine, 14–15 October, 1996.* Elsevier, Amsterdam, 1997.

30. I. Likhtarev, V. Minenko, V. Krouch and A. Bouville, Uncertainties in the thyroid dose reconstruction after Chernobyl. *Radiat. Prot. Dosim.* **105**, 601–608 (2003).

31. ICRP, Age-dependent doses to members of the public from intake of radionuclides: Part 1. Publication 56, *Annals of the ICRP,* Vol. 20, No. 2, Pergamon Press, Oxford, 1989.

32. ICRP, Age-dependent doses to members of the public from intake of radionuclides: Part 2, Ingestion dose coefficients. Publication 67, *Annals of the ICRP,* Vol. 23, No. 3–4, Pergamon Press, Oxford, 1993.

33. A. Bühl and P. Zöfel, SPSS Version 10. Einführung in die moderne Datenanalyse unter Windows. Addison-Wesley, Munich, 2000.

34. W. J. Conover, *Practical Nonparametric Statistics.* Wiley, New York, 1980.

35. A. M. Mood, F. A. Graybill and D. C. Boes, *Introduction to the Theory of Statistics,* 3rd ed. McGraw-Hill, New York, 1974.

36. H. Müller and G. Pröhl, ECOSYS-87: A dynamic model for assessing radiological consequences of nuclear accidents. *Health Phys.* **64**, 232–252 (1993).

37. R. M. Barkhudarov, K. I. Gordeev, I. K. Dibobes, I. A. Likhtarev, U. Ya. Margulis, D. P. Osanov, O. A. Pavlovskiy, B. S. Prister, M. N. Savkin and V. P. Shamov, Methodological principles of calculation of external and internal exposure of population, used while operative decision making. In *Medical aspects of the accident on Chernobyl NPP. Scientific conference materials, May 11–13, 1988* (A. E. Romanenko, O. A. Pyatak, A. Z. Zapesochnui and M. V. Shcherbakova, Eds.), pp. 111–118. Zdorov'ya, Kyiv, 1988. [in Russian]